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Overview of Power Controllable Reactor Technology

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Abstract

Consider the development status of controllable reactor, five types of power controllable reactors are introduced: mechanical controllable reactors, thyristor controllable reactor, magnetic saturation controllable reactor, transformer-type Controllable reactor and superconducting-type controllable reactor. Finally, the development of power controllable reactor technologies is prospected.

Keywords:reactor;MCR;TCR; superconduct

1. Introduction

In the 1950 s, the world's first controlled reactor was born in Britain [1], power controlled reactor and the corresponding of controlling technology had been developed. According to its technical background, controlled reactor can be divided into mechanical, electromagnetic, electronic and other type. Controllable reactor with impedance continuously adjust, which has more advantages than the traditional reactor, such as system over-voltage dynamic limiting, suppressing system circuit current, improving system stability and keeping power system from oscillation; In distribution network, with adjustable arc extinction coil, which can dynamic compensation phase-to-ground capacitive current; In power quality control and harmonic suppression domain, according to system parameters, the controllable reactor can regulate the impedance automatically to ensure the filters working in tune and making best filtering performance[2~5]。

2. Mechanical Controllable Reactor

According to reactor with core or not, it can be divided into two kinds: the air-core reactor and the core reactor. The air-core reactor inductance is not sensitive to the current changes, but to the used ferromagnetic materials; the core reactor, on the opposite, its inductance quantity changes with the current

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through it, while the ferromagnetic materials takes a little effect. Set the same inductance quantity values, the volume of the air-core reactor is much larger than the core reactor [6].

According to the electromagnetic field theory, the reactor inductance coil of volume, the geometric shape and dimension are concerned, the air-core reactor's inductance quantity is

$$L = \frac{D\mu_0 N^2 \psi}{8\pi} \tag{1}$$

Where: μ_0 is the vacuum magnetic conductivity, N is winding circle number, D is the windings of the average diameter, ψ is proportion with the ratio $\rho = r / D$ (r is the windings of the radial thickness, D is the windings average diameter, general $\rho << 1$), it can be checked by special manual.

According to reference [7], the core reactor's inductance calculation is

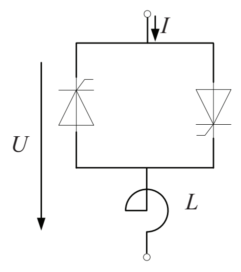
$$L = \frac{\mu N^2 A}{\delta} \tag{2}$$

Where: μ is the permeability of ferromagnetic materials, N is winding circle number, A is the cross-sectional area of core, δ is the length of magnetic circuit air gap.

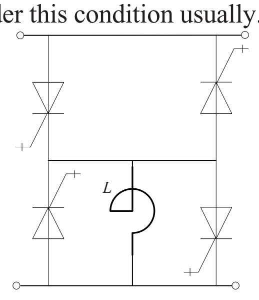
According to (1) and (2), the reactor inductance quantity is decided by many ways, such as adjusting circle number N, changing the air gap δ, changing the magnetic circuit of magnetic resistance and magnetic permeability size, adjusting the area A, etc. with the core reactor as example, the typical reactors are the moving core type, the moving coil type, the adjustable turns type, and so on.

3. Thyristor Controllable Reactor

Thyristor controllable reactor (hereinafter referred to as TCR) is, with the power electronic technology developed, a new type of controllable reactor, which widely used in reactive power and transmission lines series compensation. The basic structure of single-phase TCR consists of two antiparallel thyristor with a reactor in series, as in fig. 1(a), (b) shows, and the three-phase type used of the triangle coupling form generally. In engineering practice, under high voltage and current, it can make several thyristors in series to get an equivalent thyristor. The basic principle of TCR is by controlling thyristor trigger Angle to change the equivalent inductance quantity. Ignoring the circuit loop resistance and setting the terminal voltage crossing zero as a benchmark, the thyristors will completely conducted while the trigger Angle is 90°, and the outcome current wave is a sine form; When triggering Angle changed between $90^\circ \sim 180^\circ$, that is the TCR norm operation condition, the thyristors will not conducted completely, by adjusting the triggering angle in this scope, we can get corresponding output of equivalent reactance value; while the triggering Angle is less than 90°, which will generate direct current component in outcome current, and the current wave is not symmetrical, so don't allow TCR working under this condition usually.



(a) single-phase TCR circuit



(b) PWM controlling TCR circuit

Fig.1 Thyristor controllable reactor

According to reference [8], the relationship between the triggering angle and the fundamental current is:

$$I = \frac{\delta - Sin\delta}{\pi X_L} U \tag{3}$$

Where: U is system voltage, X_L is the serial reactor's equivalent under fundamental wave.

From (3), we can deduce (4),

$$B_L = \frac{\delta - Sin\delta}{\pi X_L} \tag{4}$$

Obviously, the relationship between triggering angle and the TCR equivalent impedance is nonlinear.

Thyristor controllable reactor can adjust reactor equivalent inductance value continuously and response quickly, the reaction time is from 10 to 20 ms, operating safely and reliably, because its work is based on the chopping circuit, which leads it to generate additional harmonics component, and brings adverse influence to the power grid. In order to overcome the disadvantages, and with the device’s characteristic of being shut off, a new kind of Thyristor controllable reactor, namely PWM control reactor [9], which based on pulse width modulation (PWM) technology, is proposed, this kind reactor developed rapidly in recent years. Its circuit topology is shown in fig. 1 (b).

The PWM control reactor utilizing four devices and a reactor constitutes H bridge type circuit, in each half wave of the system voltage, we can control the diagonal devices, which acting in complementary, to adjust the inductance.

Due to the PWM control reactor is based on the high frequency chopping PWM, comparing with TCR, its excellent advantages is that the harmonic components in outcome current is much lower, meanwhile, subject to the level of device’s shut off capacity, this kind of reactor designed capacity can not be too high.

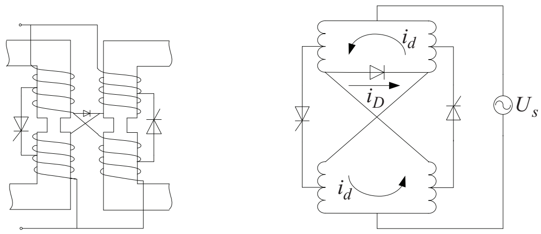
4. Magnetic Saturation Controllable Reactor

The magnetic saturation controllable reactor’s principle (this kind reactor hereinafter referred to as MCR) is that by controlling the magnetic saturation, indirectly to change the magnetic permeability of ferromagnetic materials or to change the magnetic resistance of the corresponding magnetic circuit. The characteristics of the controllable reactor is stable, reliable and flexible to control, etc [10].

Magnetic saturation type controllable reactor control winding according to whether independent can be divided into self-excited type and separately excited type; According to the relative position of the main magnetic field and control field, it can be divided into orthogonal cores type and no-orthogonal cores type. Practice, all above types are also called magnetic saturation reactor.

4.1. Self-excited magnetic saturation controllable reactor

This kind of magnetic saturation controllable reactor’s characteristic is that the winding acts not only as work winding but also the control winding. While reactor connecting to the power grid, the direct current, which controlling the saturation level of the core, can be get, by the principle of self coupling among windings. As fig. 2 shows in single phase form, we just give controlling to the thyristor rectifier, so, the self-excited direct current generates and can be adjustable. This design can do help to reduce the circuit’s loss and simplify the physical structure [11]. Self-excited MCR is a typical representative of the magnetic valve controllable reactor, which is designed by refer to the magnetic amplifiers.



(a) MCR physical structure (b) MCR circuit diagram

Fig.2 Magnetic valve controllable reactor

Magnetic valve controllable reactor's core split into two parallel parts. At the end of each core, there are windings with taps, these taps and thyristors are connected to make a full-wave rectifier. Notes: at the middle of each core, there is a sector with a small cross-sectional area. This structure design means that the core's magnetic resistance is mainly in proportion to the saturation level of this small sector, which act as like a valve, we call it a magnetic valve, and the whole device just call magnetic valve controllable reactor.

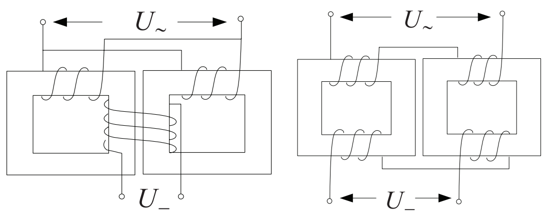
Magnetic valve controllable reactor's working principle is: in each working cycle, the two across thyristors conduct in turn, just like a full-wave rectifier, and with the diode free-wheeling, there is a DC (direct current hereafter referred to as DC) circulating current in proposed circuit, which will generate an DC magnetic bias in the core, as shows in fig.2(b), furthermore this DC magnetic bias field could cause the core tend to magnetic saturation, the existence of magnetic valve enhance the level of magnetic saturation, so , we can adjust the DC circulating current by changing the thyristors' trigger angle, which indirectly results in the corresponding change of the whole circuit's equivalent impedance. About magnetic valve controllable reactor's equivalent mathematical model or the detail control methods of DC magnetic bias can refer to [12].

In the circuit of magnetic valve controllable reactor, both the voltage and current on thyristors stay at a low and safety level, so, the capacity demand of thyristor can be low, on the other hand, the whole device's control and maintenance are relatively simply and convenient; because there is a small cross-sectional area at the middle of core, which will result in a rapidly saturated at this sector, so this special structure provided a nearly linear volt-ampere characteristics, which means low harmonic current components and low power consumption, but the existence of magnetic saturation may cause eddy-current loss on the sector of magnet yoke, which will result in some problems of the whole device such as temperature rising and vibration.

4.2. separately excited saturation controllabler eactor

Just like Magnetic valve controllable reactor's operation mechanism, separately excitation saturation controllable reactor still relay on the adjustment of DC magnetic bias to realize the wanted change of the circuit reactance value, but they are different from that the separately excitation reactor's DC control circuit is supplied by a special power circuit, namely, the control circuit and work circuit are independent [13].

Separately excited saturation controllable reactor is generally design with two core structure, according to the AC (alternating current hereafter referred to as AC) main working circuit wiring form, it can be divided into two kinds of structure: parallel and series [14], as shown in fig. 3.



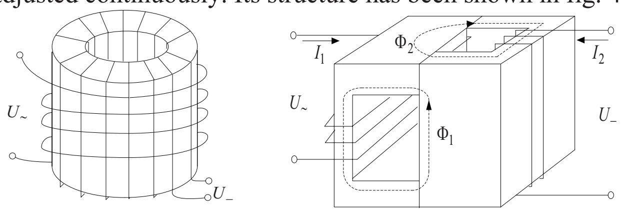
(a) parallel structure (b) series structure

Fig.3 Separately excited saturation controllable reactor

Give analysis to Fig. 3, we can get that: regardless of the wiring form of two structures, at any moment, the magnetic field direction on two coils, who is generated by DC control current, is opposite, one will enhance the working magnetic field, and the other acts as demagnetize, so, the effect on alternating magnetic field is negligible, and the AC working wave form is symmetric in each cycle, no matter parallel wiring pattern or series one. Similarly, the alternating components on DC control winding generated by coupling is quits, namely, the AC working circuit has no influence on DC control circuit, there is no coupling high voltage in DC circuit, it is helpful for reducing the insulation of the equipment and achieved better level in control characteristics.

4.3. Orthogonal cores controllable reactor

Orthogonal cores controllable reactor, which based on orthogonal magnetized theory, is a new type of controllable reactor proposed in recent years. This kind of reactor's physical structures are composed of two orthogonal AC/DC windings, through the control current on DC winding, which can change the equivalent magnetic permeability of ferromagnetic core correspondingly, thus realize that the winding inductance quantity be adjusted continuously. Its structure has been shown in fig. 4.



(a) ordinary orthogonal cores type controllable reactor

(b) orthogonal controllable reactor core

Fig.4 Orthogonal magnetic field-type controllable reactor

Fig.4 (a) is the physical structure of a general orthogonal cores controllable reactor, on the axial direction is wiring the DC controlling winding, and on the radial direction is AC working winding.

According to the deduce in [1], the relationship between the inductance on AC main winding and the DC current quantity on DC controlling winding is

$$L = L_0 - \Delta L_{\max}(1 - e^{-kI_{dc}}) \tag{5}$$

Where: L_0 is the basic circuit impedance without DC controlling current, $\Delta L_{\max}$ is the max variable quantity during adjusting circuit impedance caused by DC controlling current. k is index factor.

Fig. 4 (b) shows the physical structure of the orthogonal cores controllable reactor, which is composed of two U-shaped cores with relative position rotated 90 degrees [15]. Further analysis the distribution of magnetic flux in two cores, we can get that it can be divide into two parts: one is alternating magnetic flux generating by the AC current who has been put on one of the cores; another is DC magnetic flux generating by the DC control current. Through adjusting the level of magnetic saturation on the two cores contact surfaces by changing the DC controlling current, we can realize that the equivalent impedance on AC winding varies with the demand.

Orthogonal cores controllable reactor's advantages are: according to the position of orthogonal cores, the AC, DC windings are vertically placed, which will make two winding's coupling coefficient is near zero, so there is no induced current in dc winding, furthermore, this structure can realize electrical isolation between AC and DC circuit, which will ensure the safety in the high voltage application; In addition, both the design and the equivalent impedance control of this type reactor are depending on magnetic domain theory, which can make the reactor inductance adjustment showing a excellent linear characteristics.

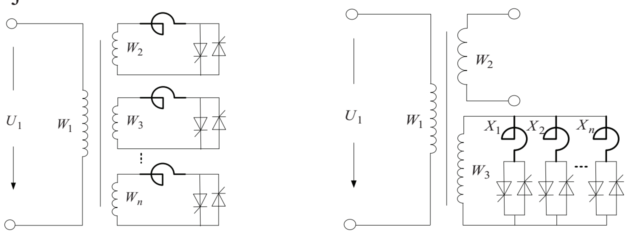
5. Transformer Controllable Reactor

Transformer controllable reactor is one of very important controllable reactor, which used widely in the electric field. This type of reactor has various form, and the names are also different, some scholars call it transformer controllable parallel reactor [16],[17], or high impedance controllable reactor and justly controllable reactor [18~21], etc.; in [24, 25], it proposed the magnetic flux controllable reactor, its working principle is different from other transformer controllable reactor, but the adjustment of circuit reactance also based on the core transformer device, so it will be divided into this category of transformer controllable reactor, and as one of the subclasses are discussed.

5.1. General transformer controllable reactor

This kind of reactor make full use of the transformer impedance transformation properties, its typical structure has shown in fig. 5. In fact, it is a special transformer with many second windings, while it running, these windings are put into short circuit state to satisfy the demand of equivalent impedance.

This kind of reactor is first proposed by the Russian scholars, as shown in fig. 5 (a), W1 is the high voltage winding on primary side of the transformer, and W2, W3... Wn is low voltage control winding on second side, each winding on the second side is composed of a pair of anti-parallel thyristor and a cascading reactor, obviously, the cascading reactor is used for the current limit. The working mechanism of transformer controllable reactor is: during the load changing from no-load to rated level, adjusting the thyristor to make each control winding work in short circuit state, which will increase the power of the reactor (note: the corresponding circuit reactance value will decrease gradually); When the first to the n-1 control winding are in short circuit state, then the next working winding should be the n control winding, namely Wn, by controlling the thyristor's triggering angle, we can realize that the equivalent circuit reactance be smoothly adjust.



(a) the height impedance reactor (b) parallel branches reactor

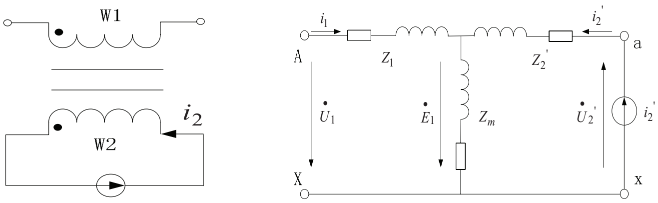
Fig.5 General transformer-type controllable reactor

Another typical structure of transformer controllable reactor is parallel branches transformer controllable reactor, which is shown in fig. 5(b). Its operation principle is same as the reactor's introduced above. The W1 is high voltage winding, which is connected to the grid, the W3 is low voltage control winding, on which is shut n branches with thyristor controlled reactor circuit; W2 winding is compensation winding, in three-phase system application, it is put into triangle to restrain the third and its times harmonic current components. The anti-parallel thyristors on each parallel branch has three states: full conduction status, turn off status, adjustable conduction status. In theory, there is 3^n states for n branches, in principle, the combinations of these states can decide a work mode, but in practice, only three of them, with excellent characteristics of control simply and cost less, are priority recommended. The three working mode include branches in turn work mode, branches choosing work mode and fixed branches work mode. The common characteristics of three models are only a branch work in the modulate state at any time [22].

To specific application, how to decide the number of shutting reactors and each branch parameters (such as: capacity and impedance) is a key step for the designing and controlling of parallel branch type controllable reactor, detail analysis and deduce may be refer to [23].

5.2. Magnetic flux controllable reactor

This type reactor is equivalent to an active control mode, and its principle wiring is shown in fig. 6 (a). among which, the transformer is the key devices, in order to make the transformer core magnetic flux changing linear, one core structure with air gap is employed. When the transformer works, its primary winding terminals AX is connected between grid and load, assumed the current flowing through it is I1, by using a voltage inverter tracking this current, and generate a opposite current injected into the transformer's second side, with altering the injected current's amplitude, the main magnetic flux in transformer changes correspondingly, so as to make the transformer equivalent impedance on primary winding terminals adjustable.



(a) physical structure (b) T model equivalent circuit

Fig.6 Magnetic flux controllable reactor

Magnetic flux controllable reactor's T model equivalent circuit is shown in fig. 6 (b). According to the reference [24], [25], the equivalent impedance on the transformer's primary winding terminals AX is

$$Z_{AX} = \dot{U}_1 / \dot{I}_1 = Z_1 - (1-\alpha) Z_m \tag{6}$$

Where: Z1 is the equivalent impedance of the transformer's primary winding, Z_m is the equivalent excitation impedance, α ($0 \le \alpha \le 1$) is the degree of compensation.

From (6), it is known that the equivalent impedance on terminals AX is variable, which is in proportion to the coefficient of compensation degree α , so by changing α , we can adjust the transformer equivalent impedance smoothly.

6. Superconducting Controllable Reactor

In power system, the superconducting controllable reactor is mainly acted as a current limiter. In order to achieving the oil current limit, its principle is by using the superconductor S-N pole transfer characteristics, which will change each coil current distribution correspondingly. During normal operation, the magnetic flux of coupling coils will be offset each other, and the coil's impedance is low, so, the current through the oil is not influenced; under fault conditions, the Superconducting components rapidly exit superconducting state, which leading to the current limit coil presents a larger impedance, and as a result, the coil current significantly be limited. In engineering practice, the most typical superconducting controllable reactors as followings: no-coupling type, three-phase type, mixed type, resistance type, transformer type, magnetic-shielding type, saturated iron core type, bridge road type and so on [26].

7. Conclusion and Prospect

As the above analyze of most typical controllable reactors, which can help us to give a full grasp about the existing control technology of controllable reactors, and provide reference for the application in power system.

In the future, with the development of power grid construction and the advancement of power science and technology, controllable reactor in power system application will play more and more important roles. The research of controllable reactor focuses on the following points:

- For specific application, based on new working principle and materials, more and more new-type controllable reactors will be developed and applied.
- The developing Controllable reactors will show characteristics such as smaller size, high capacity and low noise.
- To get more excellent performance, such as faster response and lower harmonic current components, some advanced control strategy and intelligence technology will be absorbed into the design of new type controllable reactor.

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References

[1] Xianming Mou, Jianze Wang, Yanchao Ji,Xiaoxia Wei. Present situation and development of controllable reactor [J], Electrical application, 2006, 25(4), P1-4.

[2] Tommy Holmgren, Gunnar Asplund. A test Installation of a Self-tuned AC Filter in the Konti. skan 2 HVDC link[C]//Proceedings of Stockholm Power Tech International Symposium on Electric Power Engineering, Stockholm Sweden, 1995, P582-587.

[3] Nawu Zhou, Yong Xu, Qing Zhu, Yinghao Zhu. Type Selection Analysis and Principle of New Controllable Reactor [J], Transformer, 2003, 8(40), P1-3.

[4] Sheng Zhong. Ultra high voltage transmission line with adding series compensation devices to the system problems and Solutions [J]. Power system technology, 2004, 28(6), P30.

[5] Miller J. E. Reactive Power Control in Electric System [M], New York: Wiley-Interscience, 1982, P4-56.

[6] Xiaokang Zhang. Design of adjustable 0.5 ~ 4200 mH group reactor [J] Transformer, 1993, 9, P1-6.

[7] Jitai Xu. The theory of the core reactor simulation [J],Transformer, 1995, 32(5), P2-5.

[8] Zhaoan Wang,Jun Ynag,Jinjun Liu. Harmonic control and reactive power compensation [M].Beijing: The press of mechanical industry, 1998, P164-205.

[9] Herong Gu,Xiujun Chen,Lijun Yang. New PWM control reactor and the application of reactive power compensation [J], The journal of Yanshan university, 2004, 6(28), P534-537.

[10] Dichen Liu, Baichao Chen.New controlled reactor in the application and selection of power network analysis [J], Power system technology, 1999, 23(2), P52-54.

[11] Mingxing Tian, Qingfu Li. Magnetic saturation type and transformer controlled parallel reactor [J]. The technology of high voltage, 2003, 29(7), P26-28.

[12] Mingxing Tian, Qingfu Li. Magnetic saturation type controlled reactor physical model and the equivalent mathematical model [J], The journal of electrical technology,2002, 17(4), P18-21.

[13] Zhe Liu, Ljun Jin,Qiyi Guo. The principle and design of saturation voltage controlled reactor used for the energy saving [J]. Magnetic materials and devices, 2007, 38(2), P56～58.

[14] Suli Zhang,Jianze Wang,Xianming Mou,Yanchao Ji. New low harmonic dc controlled reactor [J], Electric power system and its automation journal, 2008, 20(1), P117-120.

[15] Xianming Mou, Jianze Wang, Yanchao Ji. The principl analysis of orthogonal controlled reactor core[J], Transformer, 2008, 25(6), P27-30.

[16] Aleksandrov G. N. Controllable shunting reactor of transformer type[J], E1ektrotekhnIka, 1996, 67(10): 54-61.

[17] Mingxing Tian, Qingfu Li, Transformer controlled reactor power series of harmonic analysis and calculate[J]. The journal of chinese electrical engineering, 2003, 23(8), P168-171.

[18] Qinyong Zhou,Qiang Guo,Guangquan Bu, Liangeng Ban, Controlled reactor in our super/uhv grid application [J], The journal of chinese electrical engineering, 2007, 27(7), P1-6.

[19] Mingxing Tian, Qingfu Li. Many parallel branch type controlled reactor branch parameters are calculated [J]. The journal of electrical technology, 005, 20(20), P16-19.

[20] Mingxing Tian, Feng Zhao. Design principle and variant structure of a controllable reactor of transformer type. Proceedings of the Eighth International Conference on 2005. Vol. 3: 1780-1783.

[21] Mingxing Tian, Qingfu Li, Qunfeng Li. Calculation of current-limiting reactors and simulation analysis of a controllable reactor of transformer type. Sixth International Conference on 2003. vol. 1: 343-346.

[22] Haitao Liu,Weixing Zhang,Yu Liu,Aixing Yang. Transformer controlled reactor control winding of reactive power capacity analysis [J]. Electric power system and its automation journal,2006, 18(2): 71-72.

[23] Weixian Chen,He Chen. New high-speed response controlled reactor [J], Wuhan university of hydraulic power, 1999, 32(2), P27-31.

[24] Dayi Chen,Qiaofu Chen, Zhenchun Jia. Based on the magnetic flux controllable adjustable reactor new principle[J], The journal of chinese electrical engineering, 2003, 23(2), P116-120.

[25] Jianke Sheng,Qiaofu Chen,Yali Xiong,Yu Zhang,Dayi Li.The technology of high pressure capacity of the magnetic flux controlled type adjustable reactor [J].The technology of high voltage, 2006, 32(4), P91-94.

[26] Jianji Li. Superconducting fault current limiter [J], The journal of electrical technology, 2002, 7, P4-59.